Tracking simulation studies of the vertical emittance growth in the ATF extraction line

M. Alabau-Pons, A. Faus-Golfe, P. Bambade

LAL/RT 09-04
ATF-Report-08-14
CARE-ELAN-Document-2008-14
March 2009

Laboratoire de l'Accélérateur Linéaire

Tracking simulation studies of the vertical emittance growth in the ATF extraction line

M. Alabau Pons, A. Faus-Golfe
IFIC (CSIC-UV), Valencia, Spain

P. Bambade
LAL, Univ Paris-Sud, CNRS/IN2P3, Orsay, France

U.M.R
de
l'Université Paris-Sud

Institut National de
Physique Nucléaire et de
Physique des Particules du CNRS

LAL ~ Bât. 200 ~ B.P. 34 ~ 91898 Orsay Cedex ~ France

LAL/RT 09-0
ATF-Report-08-1
CARE-ELAN-Document-2008-1
March 2009

Tracking Simulation Studies of the Vertical Emittance Growth in the ATF Extraction Line

M. Alabau Pons[1,2], A. Faus-Golfe[1], P. Bambade[2]

1) IFIC (CSIC-UV), Valencia, Spain
2) LAL, Univ. Paris-Sud, CNRS/IN2P3, Orsay, France

Abstract

Since several years, the vertical emittance of the beam measured in the Extraction Line (EXT) of the Accelerator Test Facility (ATF) at KEK has been significantly larger than that measured in the Damping Ring (DR) itself. This long-standing problem has motivated studies of possible sources of anomalous emittance growth. One possible contribution is the non-linearity in the magnetic fields that the beam experiences while passing off-axis through the magnets shared between the DR and the EXT line. In order to quantify this effect, these magnets have been carefully modeled in terms of multipole expansions, to enable tracking simulations. Results indicate that there is significant emittance growth when the extracted beam passes with a vertical offset with respect to its reference position.

Contents

1 Introduction

The Accelerator Test Facility (ATF) at KEK (Japan) is a Damping Ring (DR) built to demonstrate the small emittance beams needed for future linear colliders [1]. It has achieved world records for the normalized vertical emittance, with values as small as 3 x 10^{-8} m rad at 1.3 GeV [1]. ATF2 is a prototype final focus system, recently completed as a result of an international collaboration to study the feasibility of focusing the damped ATF beam down to nanometer-scale spot sizes. Such small spots are required at the Interaction Point (IP) of the future linear colliders, and ATF2 uses the same principle of local chromaticity correction [2] as in the ILC and CLIC projects. One of the main goals of ATF2 is the establishment of the hardware and beam handling technologies pertaining to achieving and measuring such small beams, reproducibly and in stabilised conditions. The nominal vertical beam size is specified to be 37 nm at the ATF2 final focus point. For this, beams with the smallest vertical emittances must both be provided by the ATF Damping Ring (DR) and preserved throughout the different sections of the optical transport.

Since several years, the vertical beam emittance measured in the original EXT line of the ATF, which is also used to transport the electron beam from the ATF Damping Ring (DR) to the future ATF2 Final Focus beam line (see Fig. 1), is significantly larger than the emittance measured by a laser wire in the DR itself. There are also indications that the emittance increases with beam intensity [3]. This long-standing problem has motivated studies of possible sources for this anomalous emittance growth, as well as the study of the proper emittance process and reconstruction, which is complicated and could induce some errors in the measurement itself. One possible contribution is the non-linearity of the magnetic fields in the extraction region experienced by the beam when passing off-axis through a few magnets involved in the extraction process. From calculating the corresponding field maps for these magnets, a dominant contribution can be expected from the QM7R magnet [4].

Another study of the non-linearity in the extraction line can also be found in [5].

1.1 Non-linear Fields in the Extraction Region

The beam is extracted from the DR by means of a first kick (KICKER1 in Fig. 2), and then passes off-axis through some magnets centered on the DR reference orbit. It passes first through the so-called QM6R and QM7R quadrupoles (see Fig. 2), nominally at distances of 0.65 and 2.25 cm from their centers, respectively. Then the beam goes through three septum magnets, BS1X, BS2X and BS3X, which complete the extraction (see Fig. 2). After the extraction, there is a dispersion suppression section, with a second kicker mirroring the extraction one (KICKER2 in Fig. 2), in order to reduce fluctuations (see Fig. 3). The beam then goes through a horizontal dispersion-free zone (EX2 in Fig. 3), where five wire scanners are located in order to allow emittance measurements (MW0X-MW4X in Fig. 2). Recently, an Optical Transition Radiation (OTR) monitor was installed just after the set of septum magnets (MC1X in Fig. 2), located such that it images the beam angular spread out of QM7R, with little influence from the beam size in

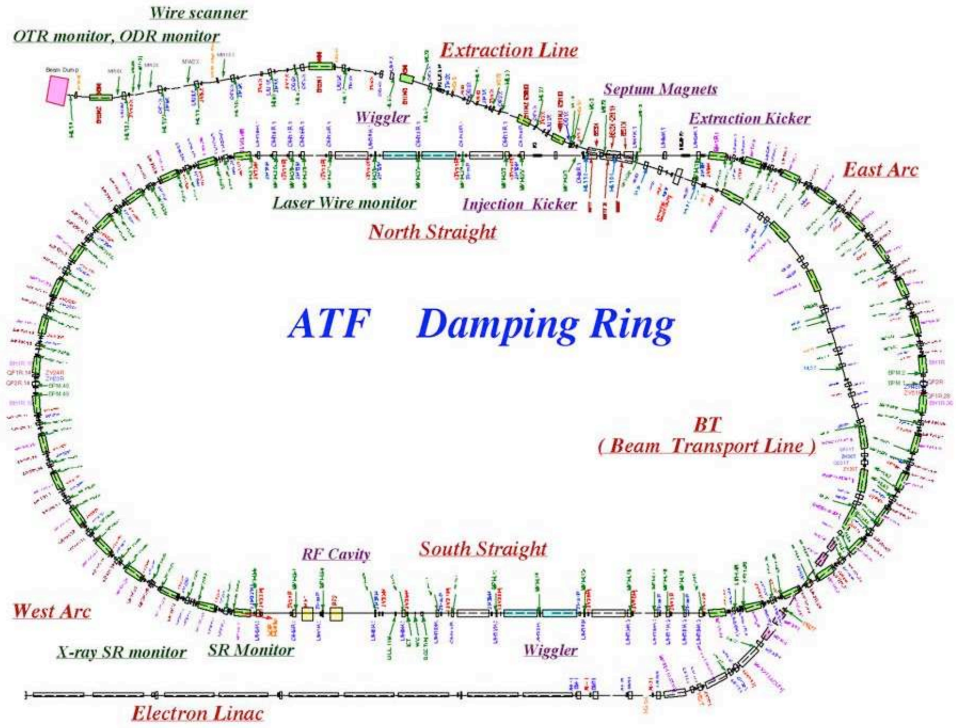

Figure 1: Schematic drawing of the ATF (Accelerator Test Facility).

QM7R, and hence can represent the growth in projected emittance from the non-linear components in QM7R quite well.
The optics of the EXT line, with the different sections EX0, EX1 and EX2, is shown in Fig. 3. The locations of the most relevant elements for the beam extraction and diagnostics are indicated.
In order to quantify the effect of the non-linearities in the magnets involved in the extraction, the computation of the magnetic field has been done with the finite element Poisson solver PRIAM [6], from the geometry of these magnets. The obtained field maps have been fitted by a polynomial function in order to get a continuous representation. More detailed information about these calculations and the corresponding multipole component list for each of the shared magnets can be found in [4]. With the purpose of studying the effect of the non-linearity when the beam passes through these magnets, simulation studies have been done. The particles have been tracked from the drift that precedes the corrector ZV9R (before KICKER1, see Fig. 2), until the OTR monitor, located after the extraction, including the multipole components calculated in [4]. The multipoles are introduced in the middle of the magnets by thin element kicks. The particles have been tracked with different vertical and horizontal displacements with respect to the ideal orbit, to study the corresponding sensitivities. Results from these tracking simulations are presented in the following sections.

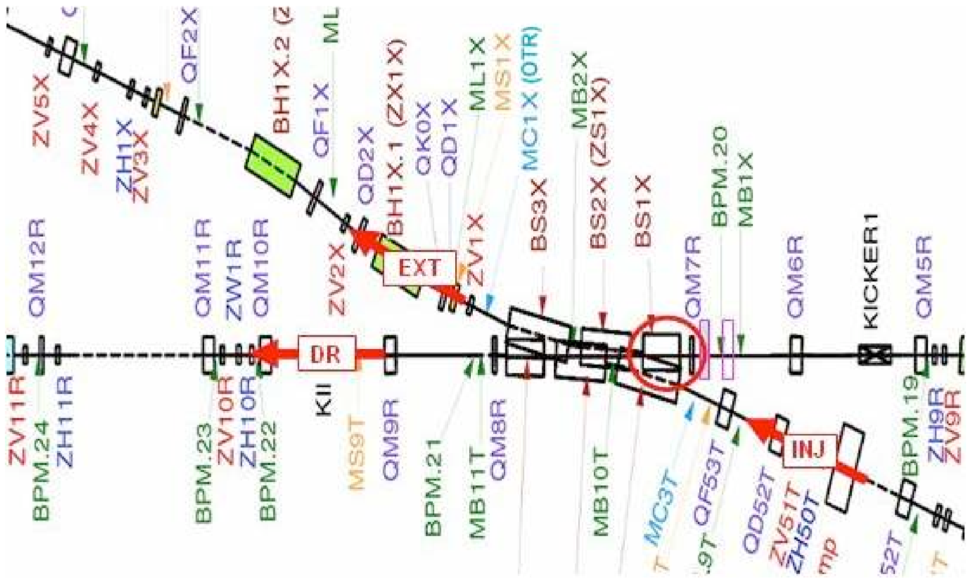

Figure 2: Schematic drawing of the extraction of the beam from ATF. The beam coming from the DR receives a first kick from KICKER1, and then passes through magnets shared with the DR, the QM6R and QM7R quadrupoles, and three septum magnets, BS1X, BS2X and BS3X. In the magnets' names, the notation "R" and "X" refers to magnets centered in the DR and in the EXT line, respectively.

2 Tracking including non-linear fields in the shared magnets between the DR and the EXT line

Simulations including non-linear fields in the different magnets of the extraction region (QM6R, QM7R and BS1X) have been performed. Transverse Gaussian beam distributions of 50000 macro-particles have been created with the code PLACET [7], using the nominal ATF2 emittances and optical Twiss parameters at the starting point of the simulations and listed in Table 1. These parameters represent the beam phase space at the beginning of the drift that precedes the ZV9R corrector which serves as starting point to create the bumps in the DR and the EXT line, just before the extraction kicker (KICKER1) (see Fig. 2). The beam has a central energy of 1.3 GeV and a flat energy distribution with 0.08% full width. The input beam phase space for the simulations are shown in Fig. 4 for each transverse plane.
The beam is then tracked through the EXT line with the code MAD [8], until the OTR monitor, located after the beam extraction. The vertical projected emittance ϵ_y at this location is obtained from the phase space as:

$$\epsilon_y = \sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle^2} \tag{1}$$

where the first moments or means of the distributions in position and angle have been substracted, and the averages are taken over the distributions of the beam particles [9].

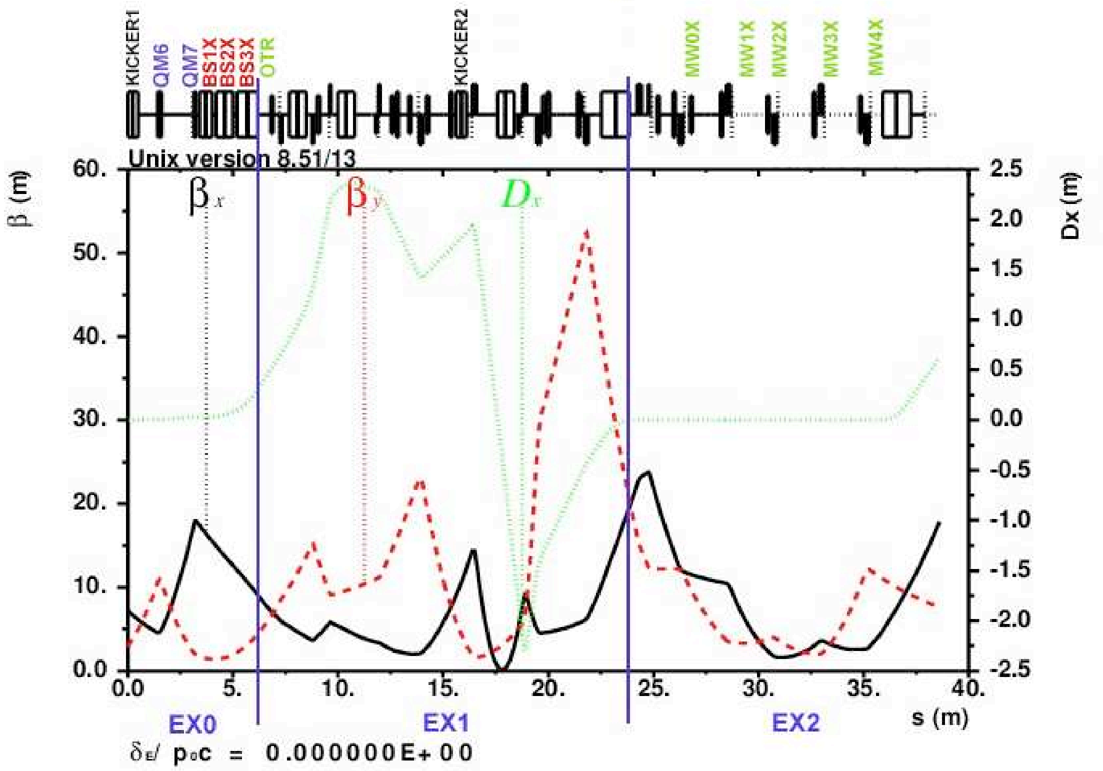

Figure 3: Optics of the ATF EXT line. The line is divided in the extraction region (EX0), the dispersion supression section (EX1), and the diagnostic section (EX2).

Vertical beam sizes and vertical projected emittances at the OTR, as a function of the vertical bump amplitude in the QM7R magnet are shown in Fig 5. The results of the simulations are shown for different cases: without any multipolar component in the magnets involved in the extraction, and including successively the multipole components in QM6R, QM7R and BS1X.

Without including in the simulation any non-linear multipolar component for the involved magnets, (red line in Fig. 5), the beam sizes and emittances are rather constant with the vertical offset.

As expected, the same occurs when including the multipolar components predicted in [4] for the QM6R quadruple, (green line in Fig. 5), since the nominal horizontal extraction position of the beam is very close to the center of the magnet, and the resulting non-linearity is hence small.

However, a significant increase occurs with the bump amplitude when including the QM7R multipolar components (dark blue line in Fig. 5), as the extracted beam passes off-axis horizontally significantly beyond the linear region of that magnet.

Fig. 6 shows the beam phase space at the OTR location corresponding to a 1 mm vertical bump in QM7R, for the cases in which no multipoles (green points) and QM7R multipoles (red points) are included in the simulation. The volume occupied by the beam

Table 1: Input beam emittances and Twiss parameters for the tracking simulations corresponding to the location just before the ZV9R corrector.

E (GeV)	1.3
$\delta p/p$ (%)	0.08
ϵ_x (pm·rad)	1200
ϵ_y (pm·rad)	12
β_x(m)	2.06210
β_y(m)	2.92901
α_x	-3.51293
α_y	1.15084
D_x (m)	-1.096×10^{-3}
D'_x	-1.691×10^{-3}

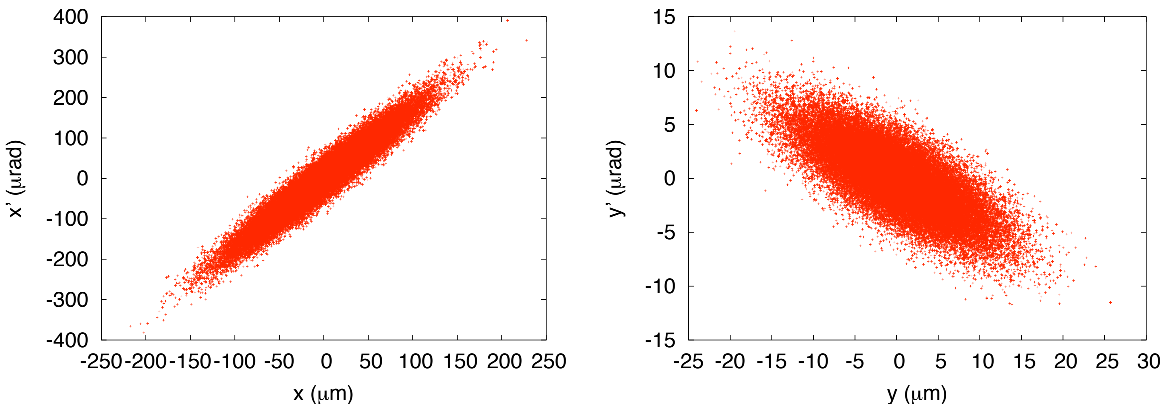

Figure 4: Transverse phase space of the input beam used for the simulations. The input distribution corresponds to the entrance of the drift that precedes the ZV9R corrector.

in the vertical phase space increases significantly when QM7R multipoles are included. When including the multipole components for the BS1X septum magnet predicted in [4], (pink line in Fig. 5), almost no difference is found with respect to the simulation including the QM7R multipoles, as the predicted sextupolar component for BS1X is relatively small. About a 5% difference is found for a 1 mm bump amplitude.

3 Tracking simulation for different vertical and horizontal bumps in the extraction region

Tracking simulations have been also done with vertical and horizontal bumps only, and with combined horizontal and vertical ones. Results are summarized in Fig. 7. For

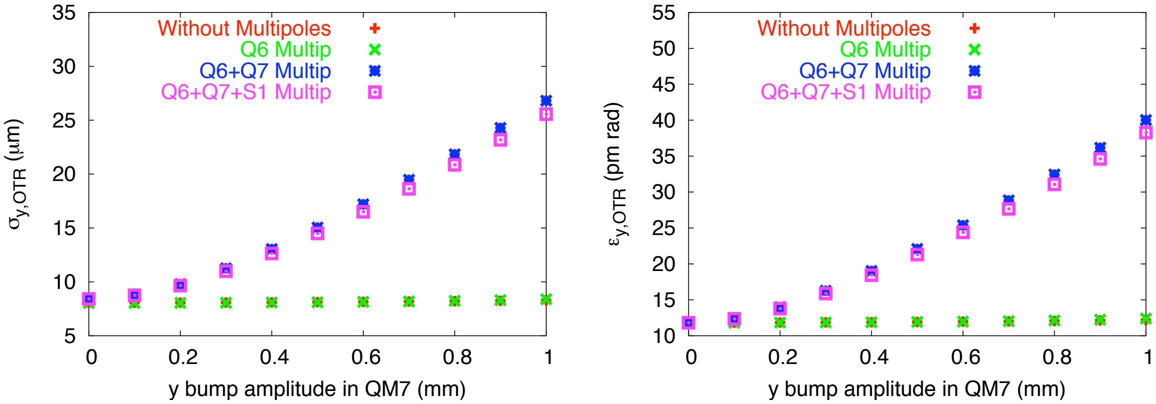

Figure 5: Vertical beam sizes and vertical projected emittances at the OTR location as a function of the vertical bump amplitude in the QM7R quadrupole including non-linear fields in the different magnets of the extraction region.

± 1 mm vertical bumps in QM7R (Fig 7 left, top), there is a significant increase of the vertical projected emittance, while in the case of ± 1 mm horizontal bump with the beam centered vertically (Fig. 7 right, top), the increase is still negligible.
As shown in Fig. 7 bottom left, having an additional horizontal bump of half a millimeter increases the emittance growth as a function of the vertical bump amplitude. In the case of a vertical bump of half a millimeter, the emittance growth for a $+1$ mm horizontal bump becomes important, while for a -1 mm horizontal bump the projected emittance decreases since the beam goes towards the center of the quadrupole, that is towards the linear region (see Fig. 7 bottom right).

4 Projected emittances at different locations along the EXT line

Furthermore, tracking simulations have been carried out to obtain the projected emittances at different locations along the extraction line: before and after QM7R, at the OTR position, and at the location of the four wire scanners available in the diagnostic section, MW0X, MW1X, MW2X and MW3X. Results as a function of the vertical bump in QM7R are shown in Fig. 8.
Before the magnets where the non-linear fields arise, the projected emittance is rather constant with the bump amplitude, while it increases after the extraction. It is not significantly increased along the EXT line where the different wire scanners are located.

5 Conclusion

Tracking simulations along the EXT line including the non-linearities of the magnetic fields of the magnets involved in the extraction have been done in order to quantify the

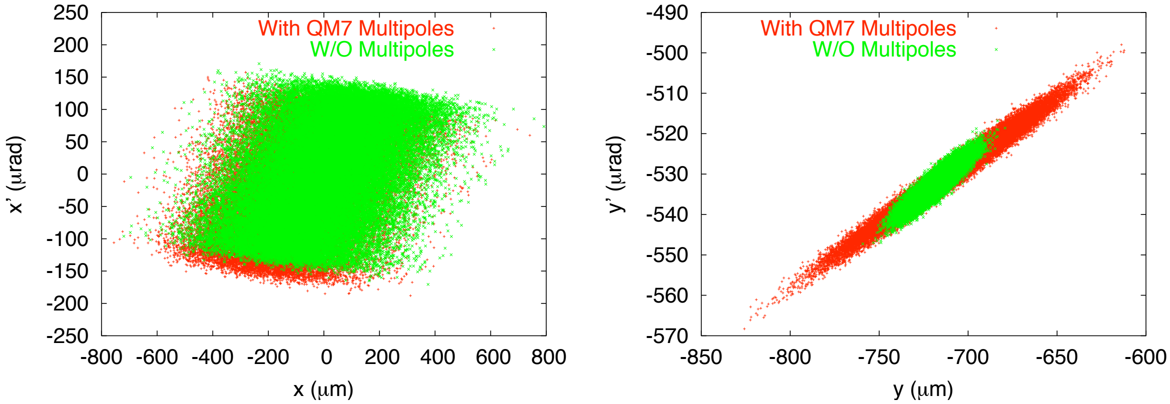

Figure 6: Transverse phase space of the beam at the OTR location corresponding to 1 mm of vertical bump amplitude in QM7R, for the cases in which no multipoles (green points) and QM7R multipoles (red points) are included in the simulation.

effect on the extracted beam emittance.
It was found that the main non-linear effect arises from the QM7R quadrupole. The non-linearity in this magnet would have negligible effect if the beam were always centered vertically. As was found in [5], it however causes significant growth of the effective vertical emittance as soon as the beam goes through vertically off-axis.
The orbit stabilization in ATF achieves levels of about 100 μm, but the beam orbit itself can arrive to the QM7R quadrupole with displacements of a few mm, because of systematic orbit distortions in the DR. Such distortions can be expected from mechanical drifts between re-alignments and from known imbalances in the configuration of bending magnets, which are only partly corrected at present.
Combined vertical and horizontal displacements cause increased effects when going towards the outer part of the quadrupole magnet, while it reduces them as expected when going towards the linear region around its center.
As the simulations show that the beam is very sensitive to the magnitude of the non-linear field in QM7R, and that these fields can change significantly not only with the vertical orbit, but also with the horizontal one, the ATF2 collaboration recently decided to exchange the QM7R quadrupole for another one with a larger aperture, in order to mitigate these effects and reduce the sensitivity to the injection orbit.

Acknowledgements

We thank the ATF group at KEK for their help and support, and we acknowledge useful discussions and collaboration in the regular meetings of the "ATF EXT anomalous emittance" task force, in particular with Robert Appleby, Julien Brossard, Shigeru Kuroda, Cecile Rimbault, Anthony Scarfe and Mark Woodley.

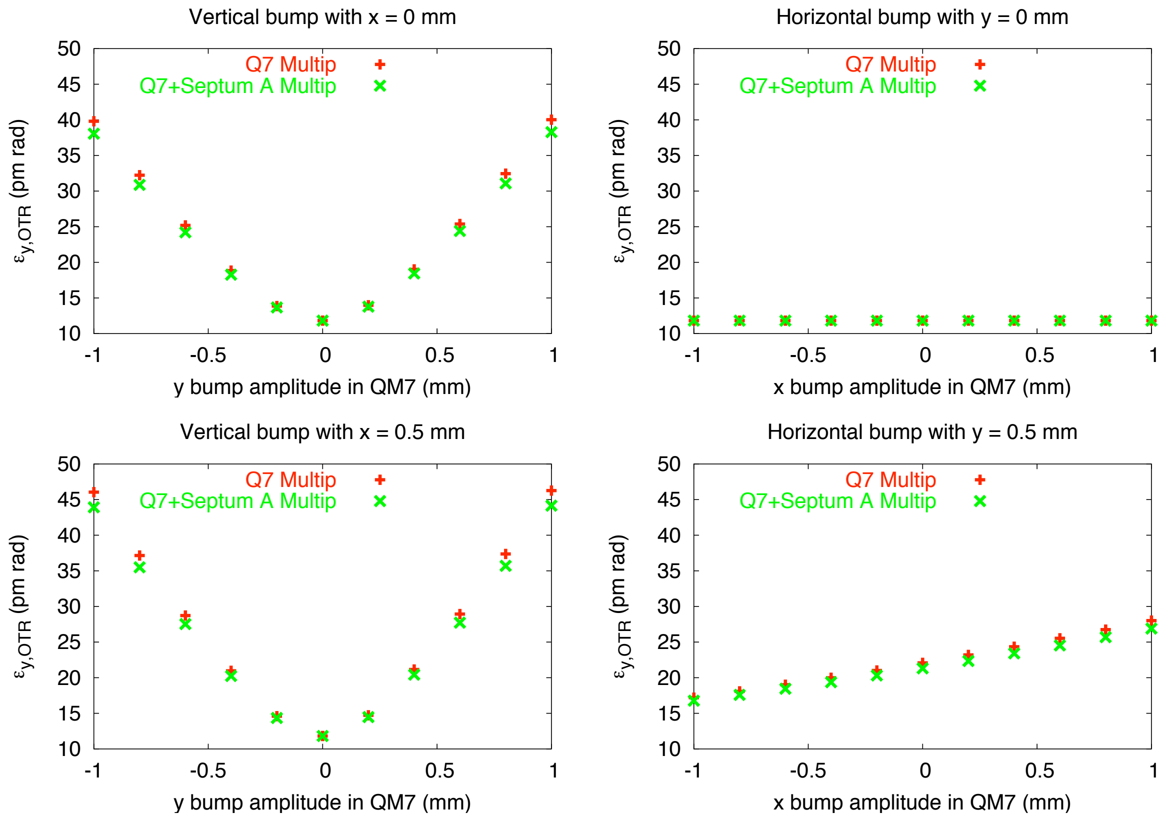

Figure 7: Vertical projected emittances at the OTR location as a function of combined vertical and horizontal bump amplitudes in the QM7R quadrupole. Simulations performed for three cases, including non-linear fields in different magnets of the extraction region.

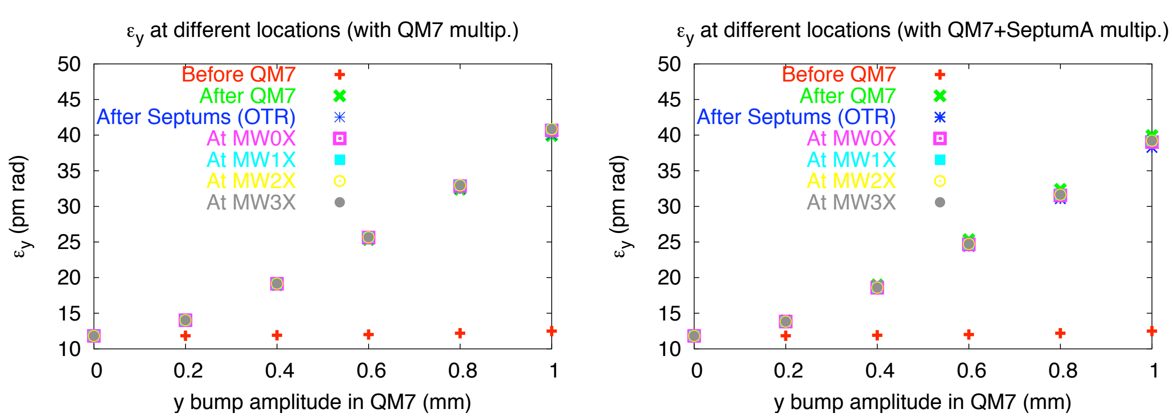

Figure 8: Vertical projected emittances at the OTR location as a function of combined vertical and horizontal bump amplitudes in the QM7R quadrupole. Simulations performed for three cases, including non-linear fields in different magnets of the extraction region.

References

[1] "ATF Report". Study report JFY 1996-1999, http://atfweb.kek.jp./atf/Reports/ATF99new.pdf.

[2] ATF2 Proposal, Vol. 1 & 2. ATF2 Collaboration, August 11 2005 and February 13 2006, http://lcdev.kek.jp/ATF2/proposal

[3] J. Nelson, M. Ross, M. Woodley, "ATF Studies; Extraction line dispersion, beam stability and bunch length sensitivity etc", June 2000. ATF-00-06 Internal Report.

[4] M. Alabau Pons, A. Faus-Golfe, P. Bambade, G. Le Meur, F. Touze, "Modeling of the shared magnets of the ATF Extraction Line". CARE/ELAN Document-2008-013, ATF-08-13 Internal Report.

[5] F. Zhou, J. Amann, S. Selestky, C. Spencer and M. Woodley, "Simulation studies on the Vertical Emittance Growth in the Existing ATF Extraction BeamLine", SLAC-PUB-12892 December 2007.

[6] G. Le Meur, F. Touze, "PRIAM / ANTIGONE a 2D 3D package for Accelerator Design", EPAC 94.

[7] D. Schulte, A. Latina, N. Leros, P. Eliasson and E. D'Amico. The Tracking Code PLACET, https://savannah.cern.ch/projects/placet.

[8] H. Grote and F.C. Iselin, "The MAD program (Methodical Accelerator Design) version 8.16, User's reference manual", CERN/SL/90-13(AP), (rev. 4), (March 27, 1995).

[9] M.G. Minty, F. Zimmermann, "Measurement and Control of Charged Particle Beams", Springer (2003).